Exploring Many Flavor QCD with Wilson Fermion

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based on collaboration with

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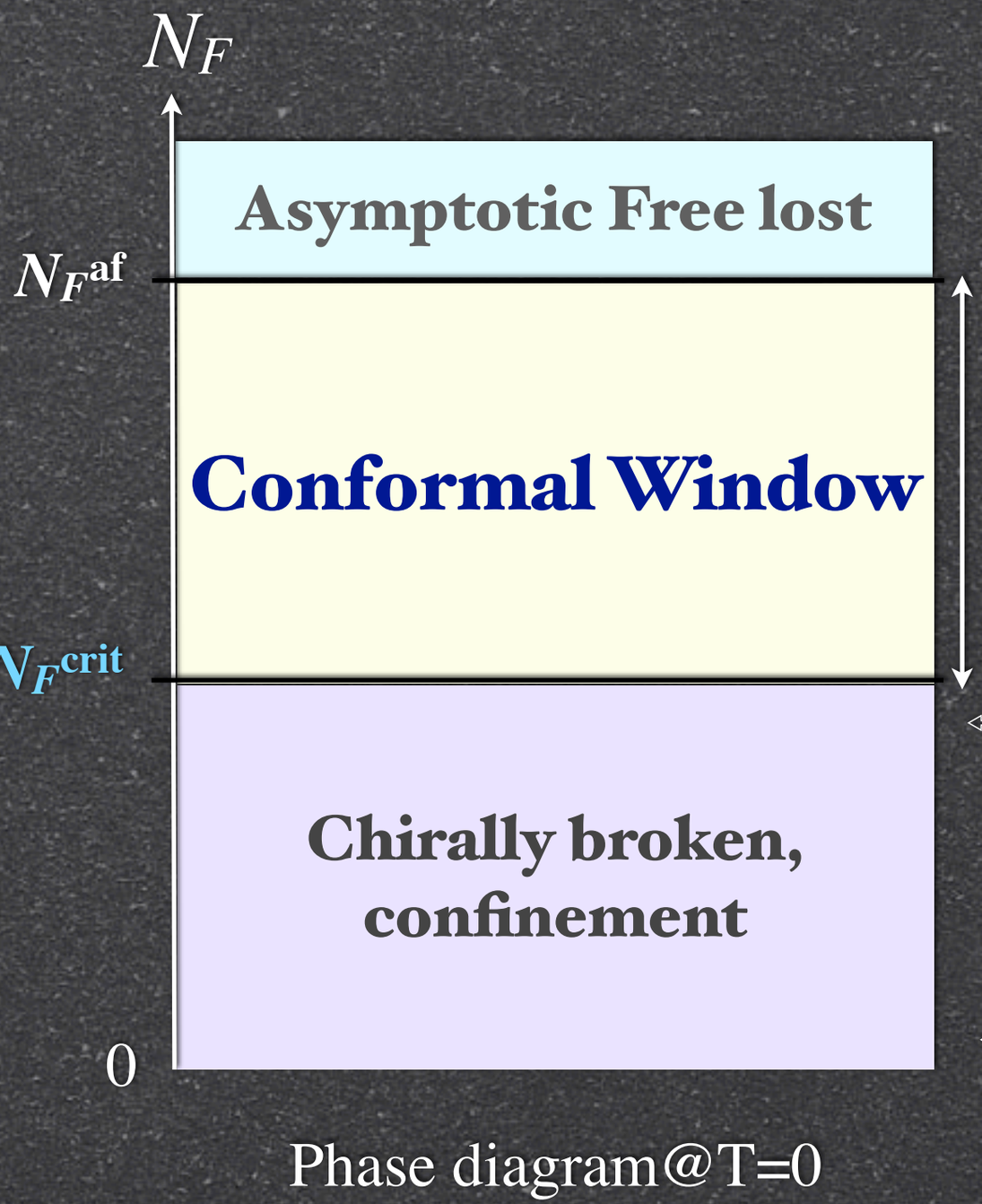
Conformal Window

Phase of a theory with N_F degenerate massless flavors at T=0



Phase diagram@T=0

Conformal Window:
$N_F^{crit} < N_F < N_F^{af}$

Viable Technicolor model (e.g. WTC) is expected to exist in vicinity of N_F^{crit}.

First task : Identifying N_F^{crit}

We take Wilson fermion.

Disadvantages:

✓O(a) scaling violation

✓Fine-tuning,

✓...

Advantages:

✓Simple, tractable and well understood

✓Able to study arbitrary N_F without any subtlety

✓Independent check to KS (or other) results

Contents

There are several approaches to identify N_F^{crit}.
Focusing on SU(3) gauge theory, we are performing the following studies:

1. Running coupling and anomalous dimension in 10-flavor QCD. IRFP?

2. Finite temperature study of Many Flavor QCD ($N_F = 6$ - 10)
   - Strategy
   - Future prospect

$\alpha(\mu)$ and γ_m in 10-flavor QCD

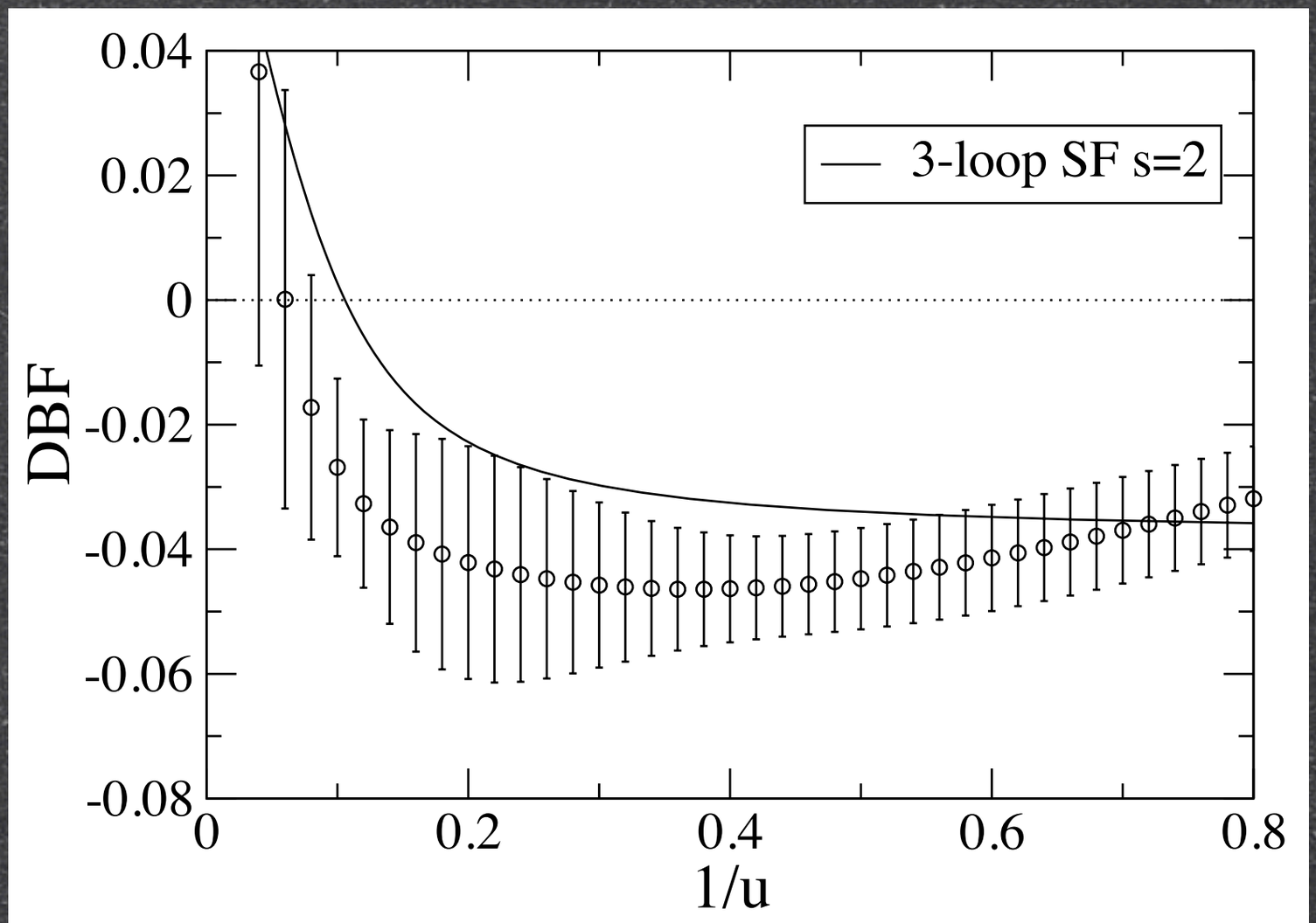
M. Hayakawa, K.-I. Ishikawa, Y. Osaki, S. Takeda, S. Uno, NY

$g_{SF}^2(\mu)$ in 10-flavor QCD

Hayakawa, Ishikawa, Osaki, Takeda, Uno, NY, PRD(2011) and work in progress

$$B^{\mathrm{SF}}(u,s) = \frac{1}{g^2_{\mathrm{SF}}(u,s)} - \frac{1}{u}$$

Preliminary



DBF=0 ⇒ IRFP

$g^2_{FP} \geq 12$

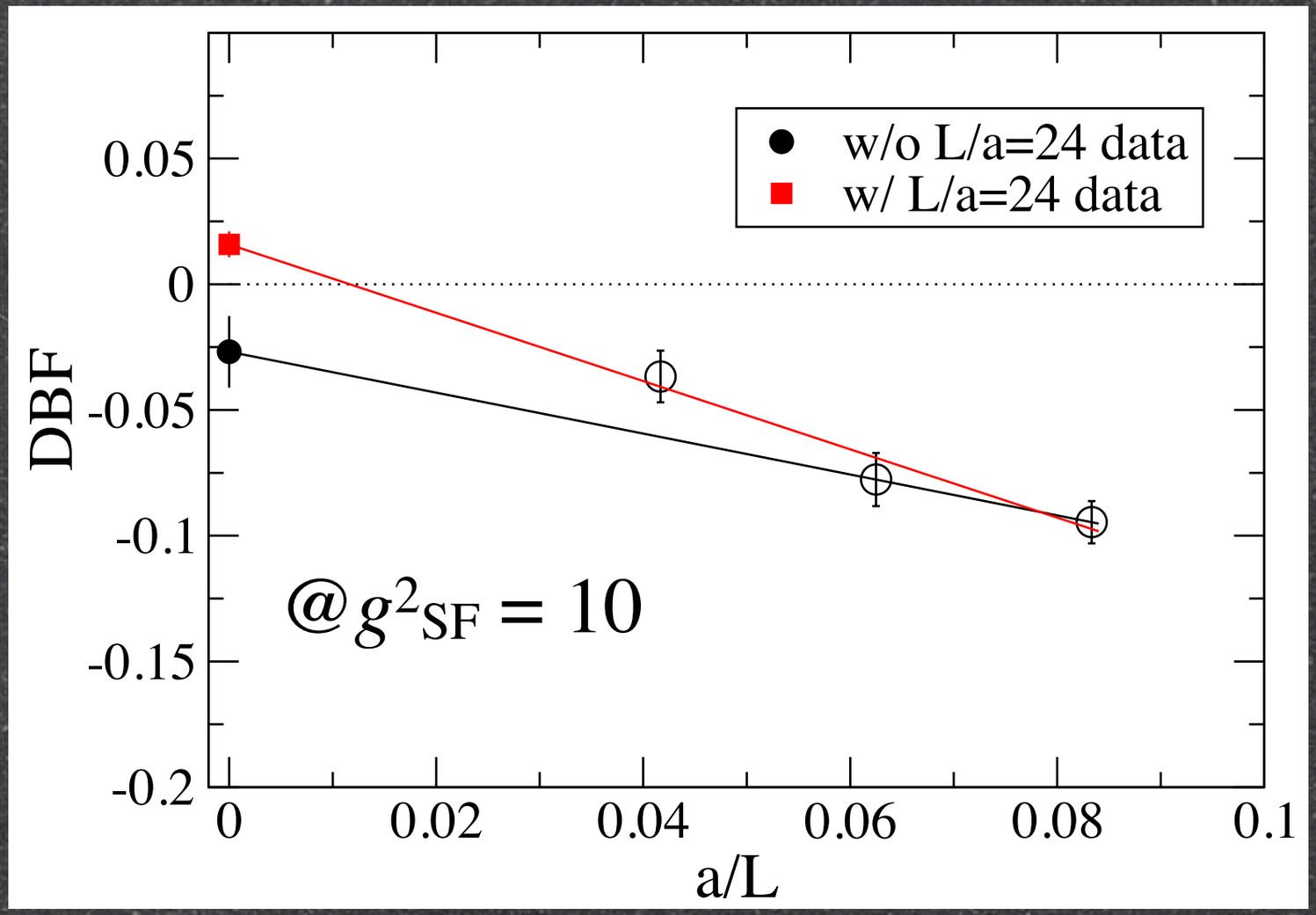
Continuum extrapolation with two data points.

In order to have more confidence, large V calculation is on-going.

$g_{SF}^2(\mu)$ in 10-flavor QCD

Hayakawa, Ishikawa, Osaki, Takeda, Uno, NY, PRD(2011) and work in progress

Preliminary



Adding large V data, the continuum limit shits upward.

$g^2_{FP} \geq 12 \Rightarrow g^2_{FP} \sim 10$

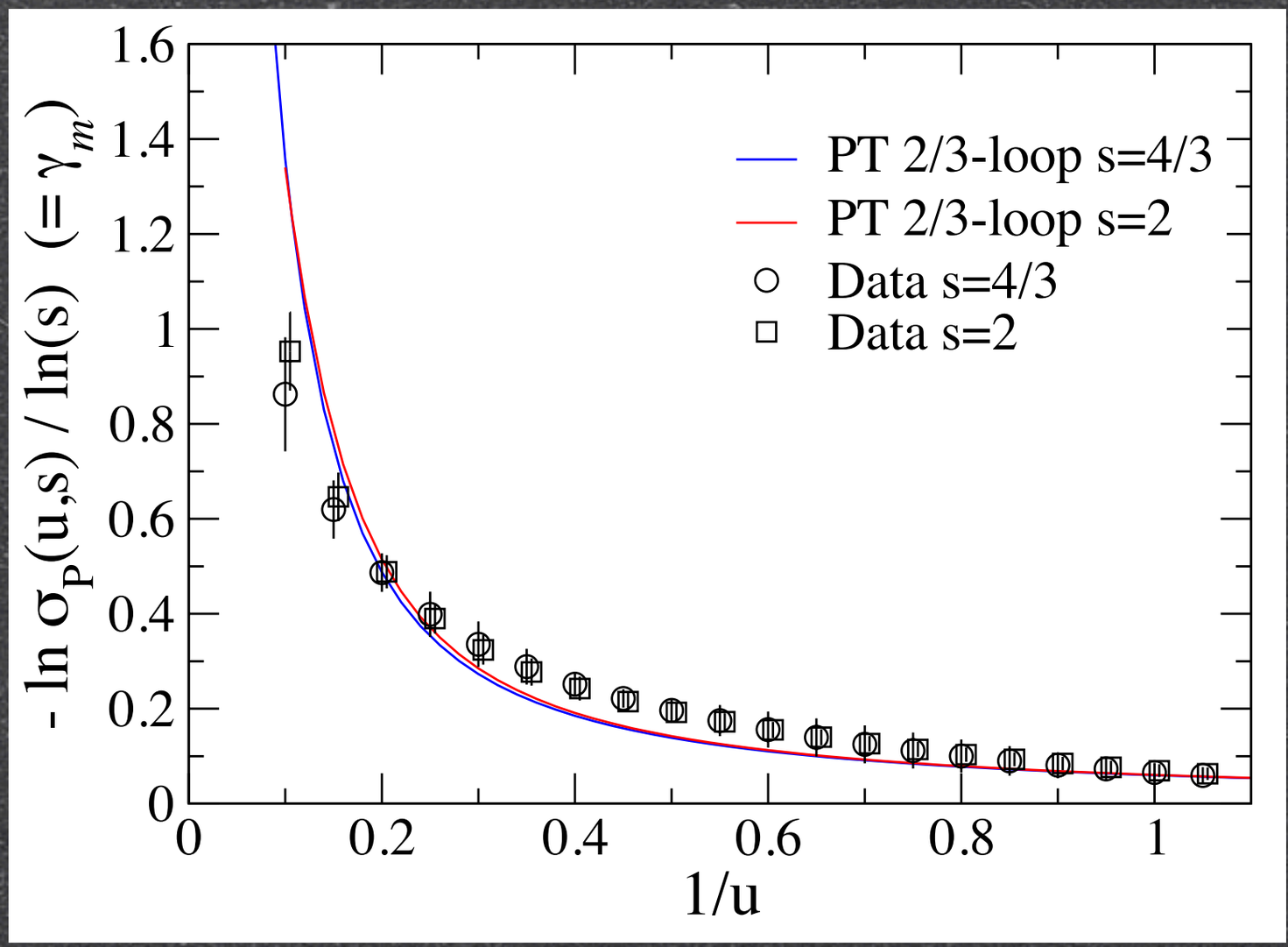
⬇

More confident on IRFP

γ_m of 10-flavor QCD

Hayakawa, Ishikawa, Osaki, Takeda, Uno, N.Y., work in progress

Preliminary



Two different step scaling factors give consistent result.

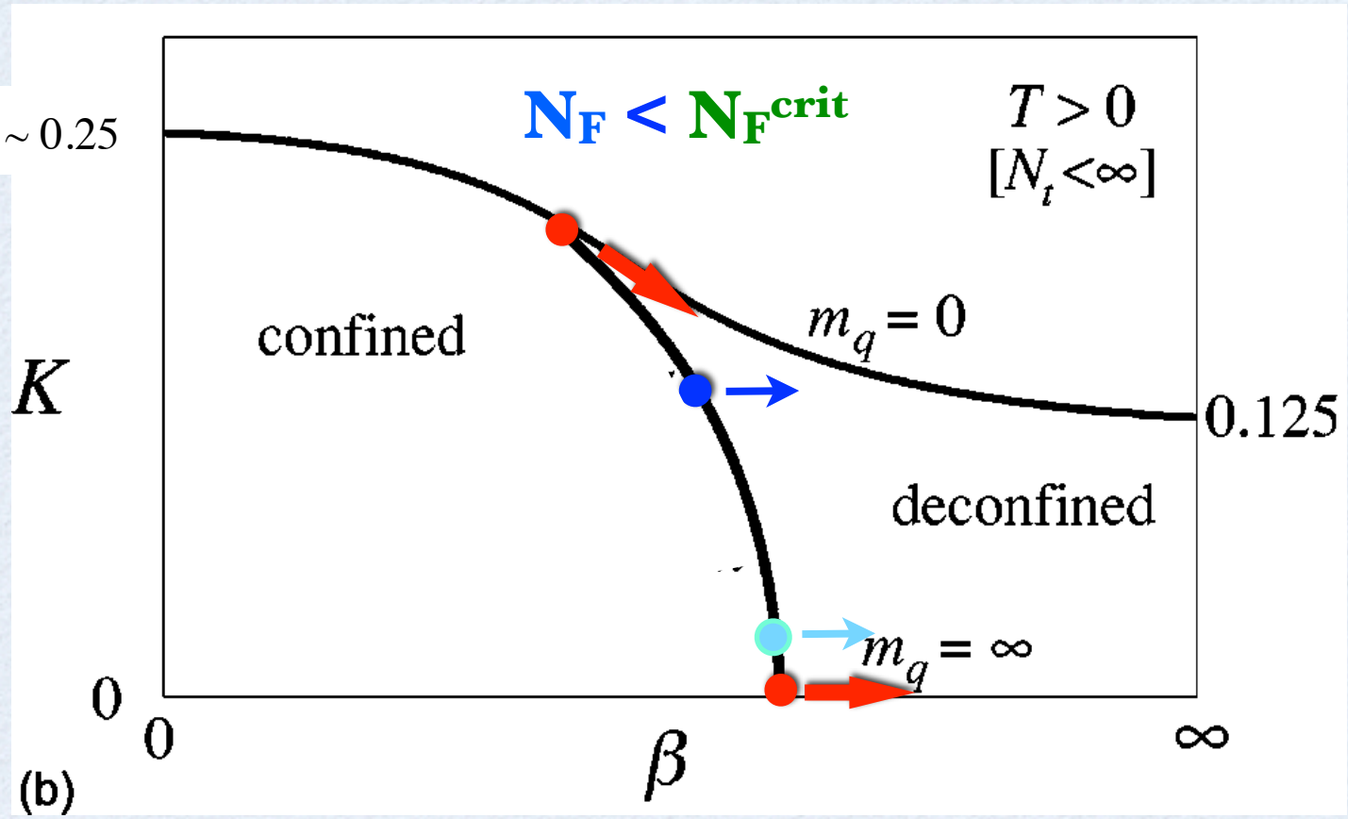
Assuming $g_{FP}^2 \sim 10$, $\gamma_m \sim 1$!

10-flavor QCD appears to be in CW ($N_F^{crit} < 10$) and have $\gamma_m \sim$ O(1).

Finite temperature study of Many Flavor QCD

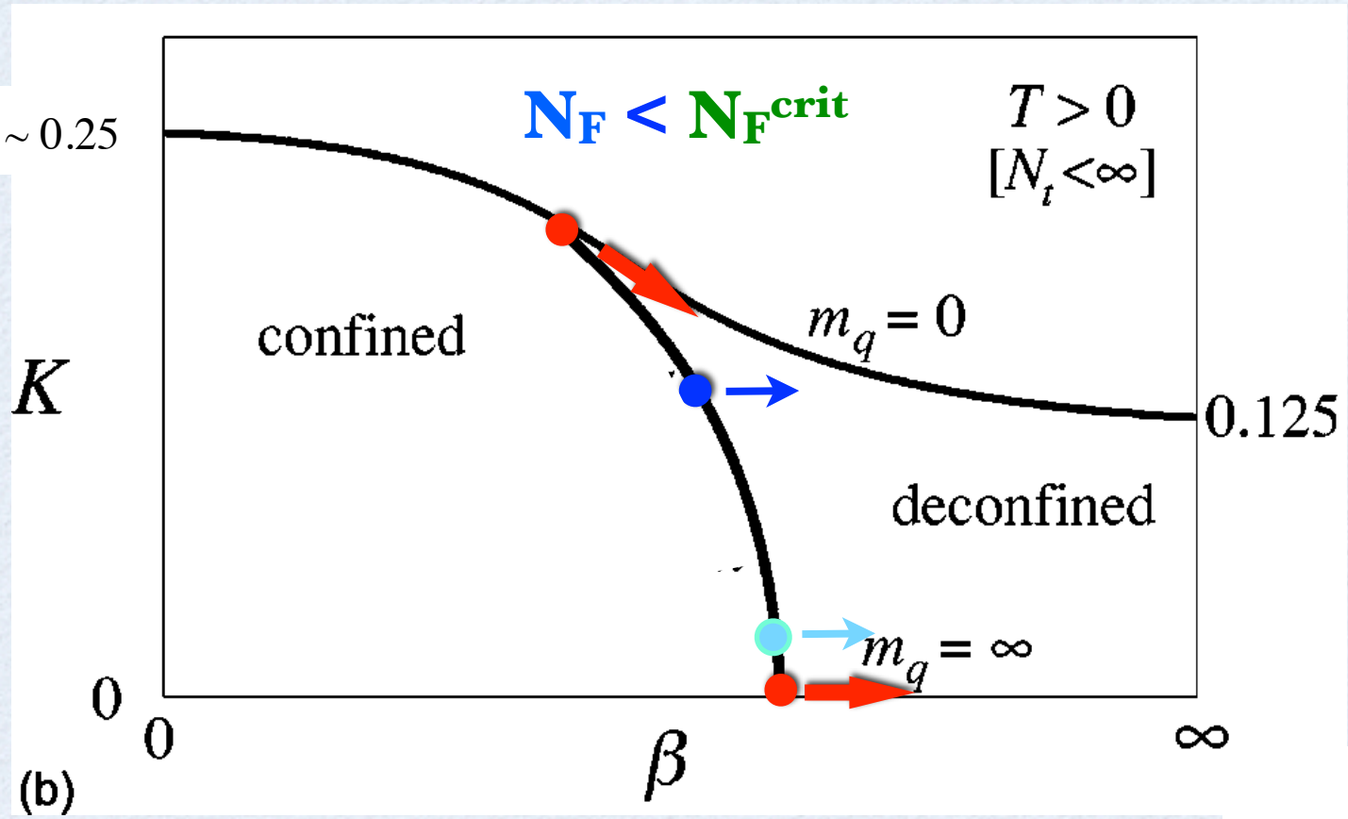
WMF Collaboration: **M. Hayakawa, K.-I. Ishikawa, Y. Iwasaki, S. Takeda, T. Yoshie, NY**

Phase diagram of Wilson fermion for $N_F < N_F^{crit}$ Iwasaki et al. (91,04)



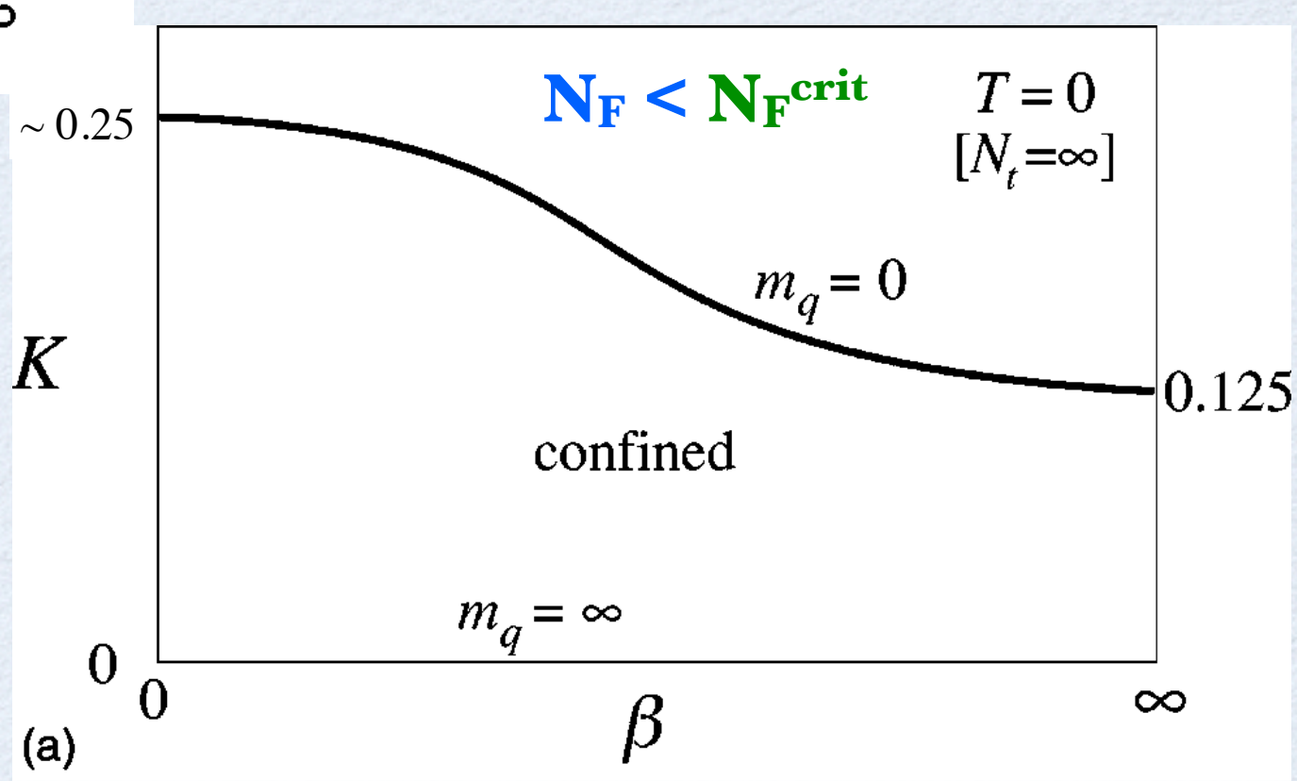
If the theory is confining, the transition line move to the right as T decreases (or V increases).

Phase diagram of Wilson fermion for $N_F < N_F^{crit}$ Iwasaki et al. (91,04)

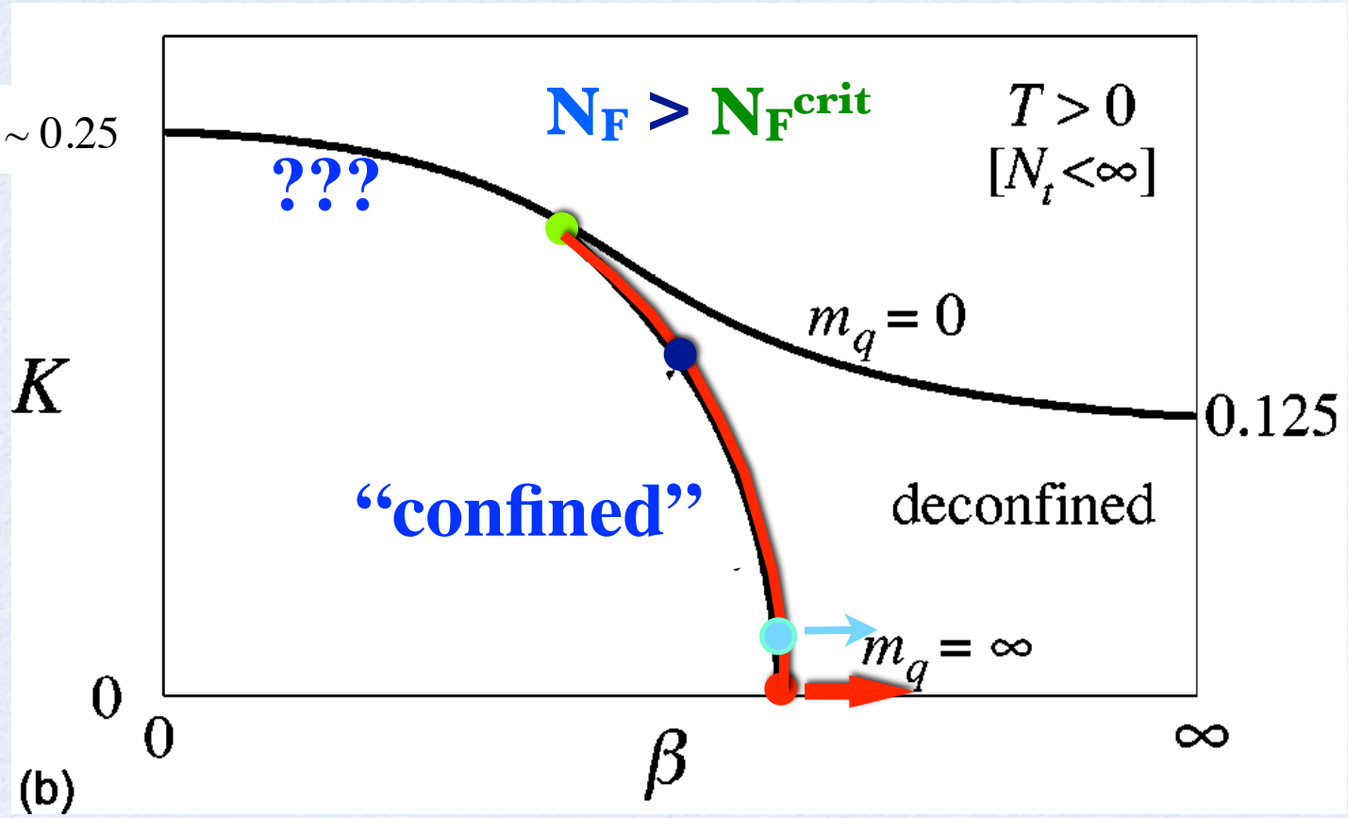


If the theory is confining, the transition line move to the right as T decreases (or V increases).

Eventually, the whole region is covered by confining phase.

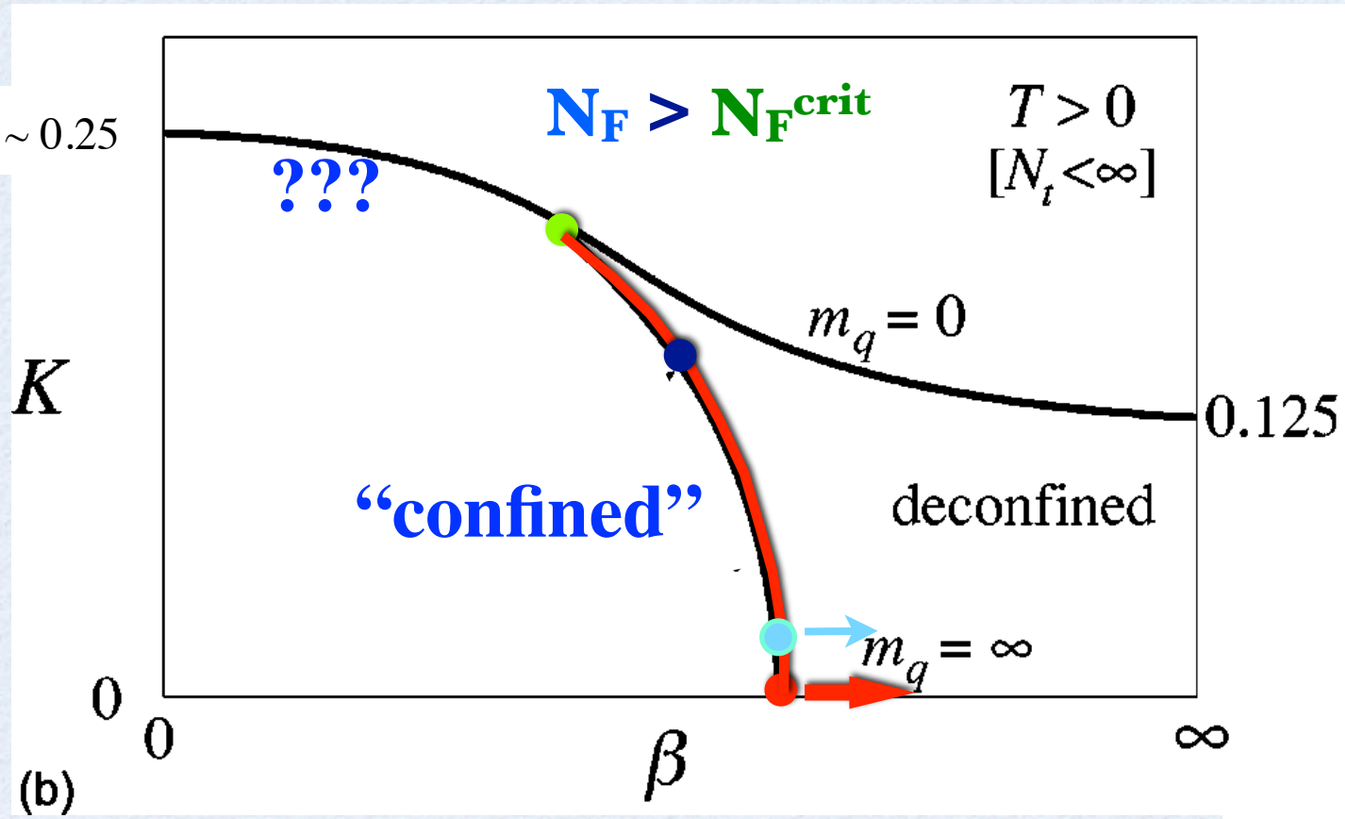


Phase diagram of Wilson fermion with $N_F^{crit} < N_F < N_F^{af}$ (speculation)



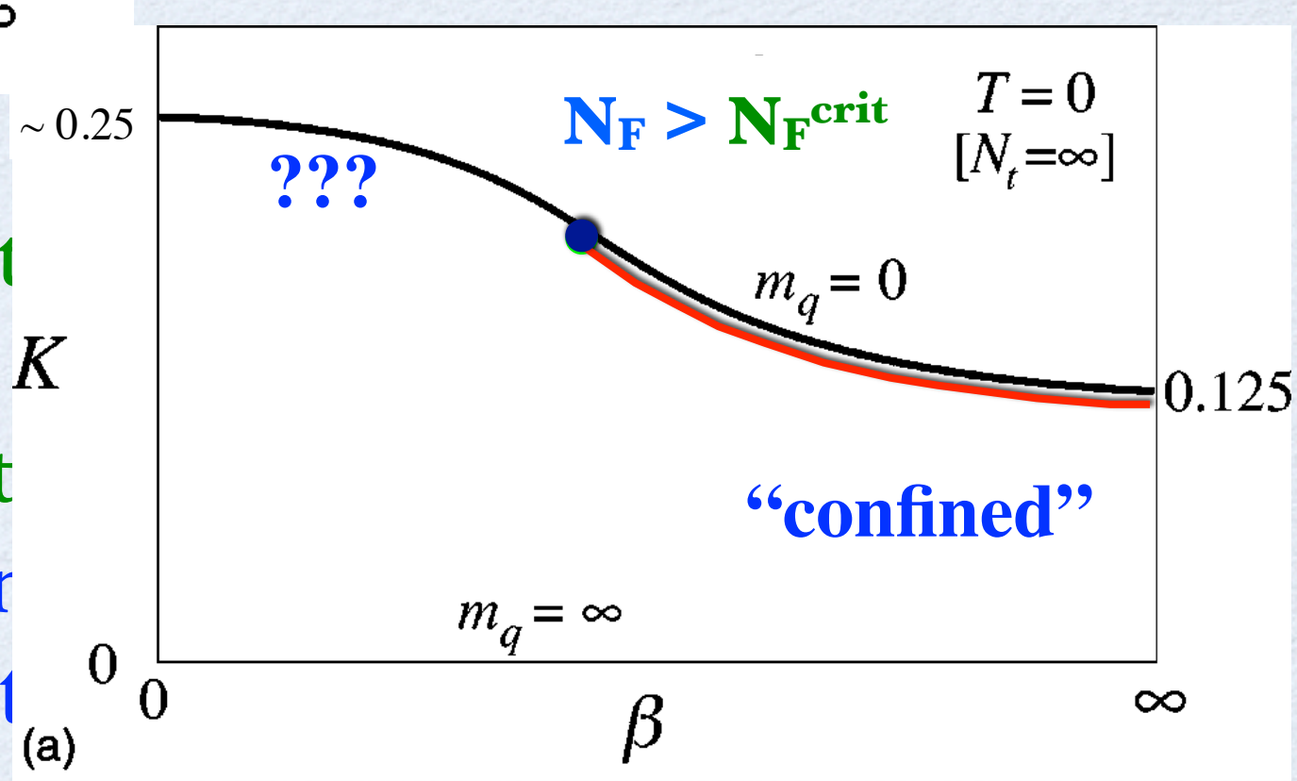
The one end of the transition line at $m_q=\infty$ moves to the right with V as before, while the other end at $m_q=0$ won't.

Phase diagram of Wilson fermion with $N_F^{crit} < N_F < N_F^{af}$ (speculation)



The one end of the transition line at $m_q=\infty$ moves to the right with V as before, while the other end at $m_q=0$ won't.

In the large V limit, the relevant region is covered by "confined" phase except for the chiral limit. In **"confined"**, Λ_{TC} depends on m_q and vanishes in the chiral limit.

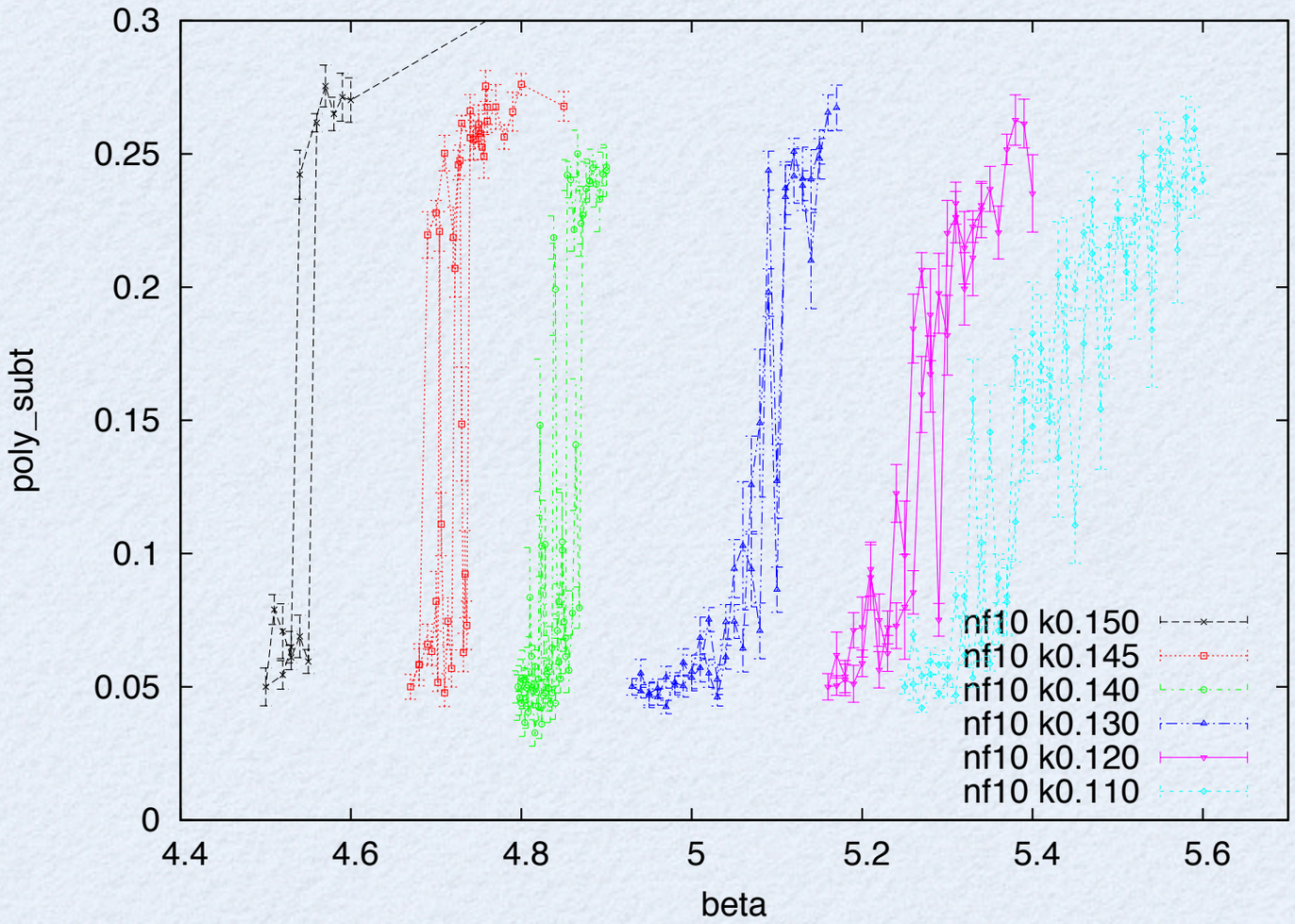


General Strategy

- ✓ Find **the critical endpoint around m_q=0**.
- ✓ Keep monitoring it while changing V to see whether it moves to the right with N_T or V.
- ✓ If the endpoint moves to the right as in QCD, the theory is outside of Conformal Window.

This work (N_F=10)

m_Q and β dependence of Polyakov loop@N_F=10



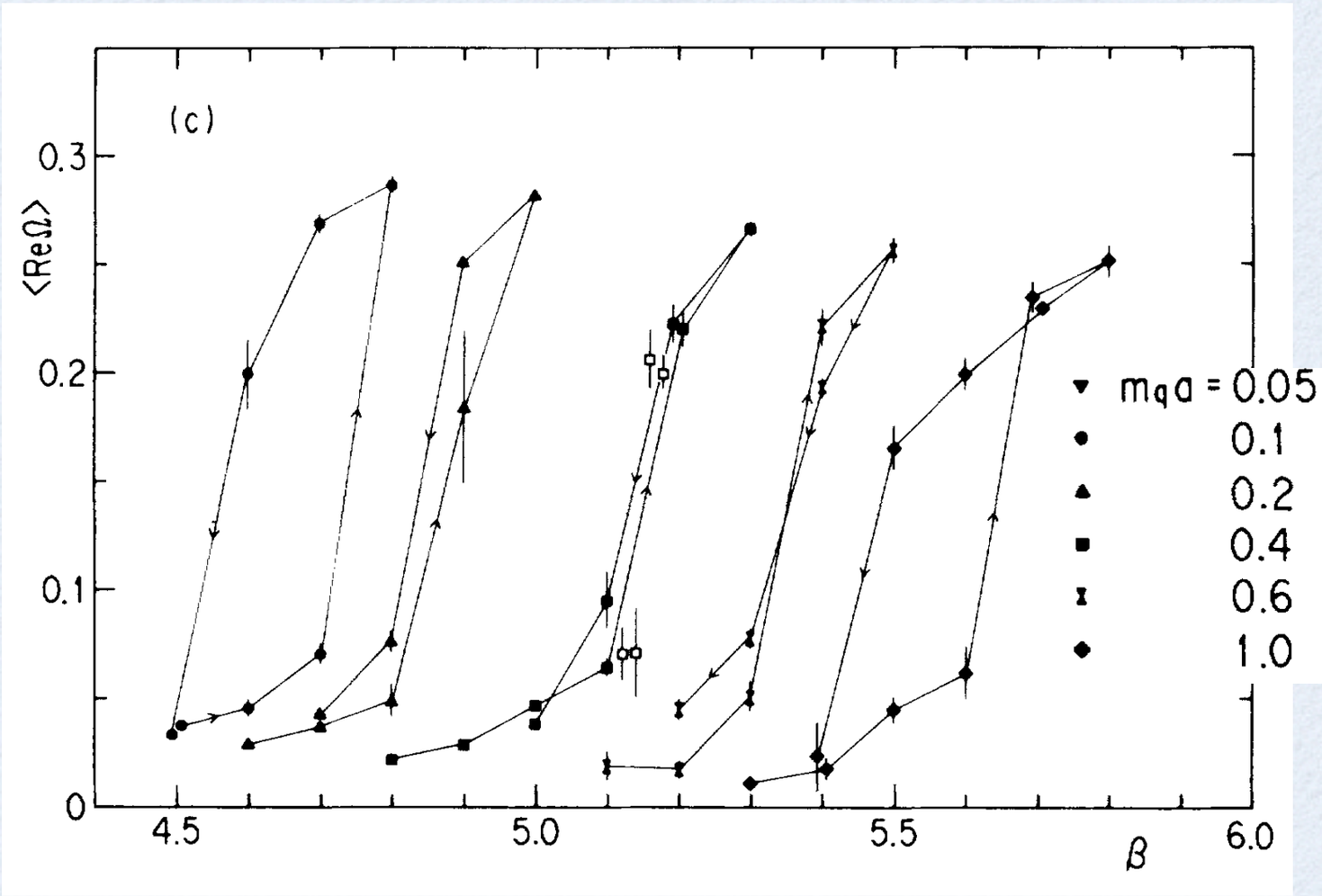
This work using Wilson Fermion on V=4^3x4.

1st oder weakens as going to small kappa.

Previous Results (N_F=10)

Fukugita, Ohta, Ukawa (88)

m_Q and β dependence of Polyakov loop@N_F=10



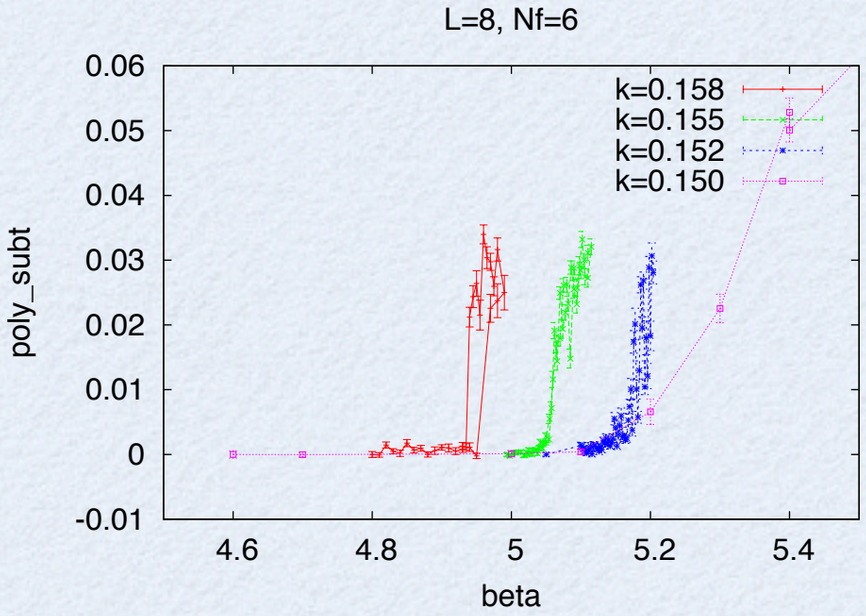
KS, V=8^3x4.

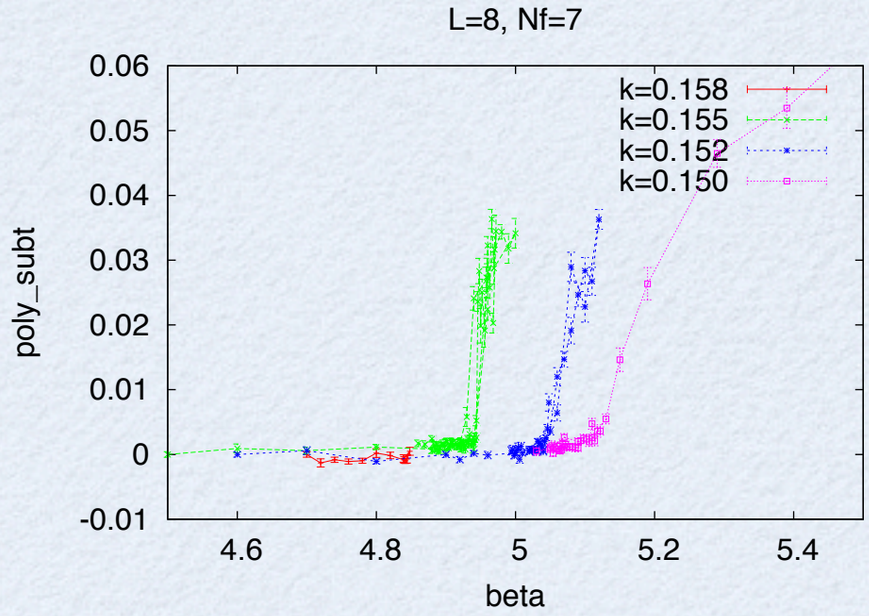
Observation:

Transitions are 1st order over the entire range of fermion mass at N_F=10. No end point.

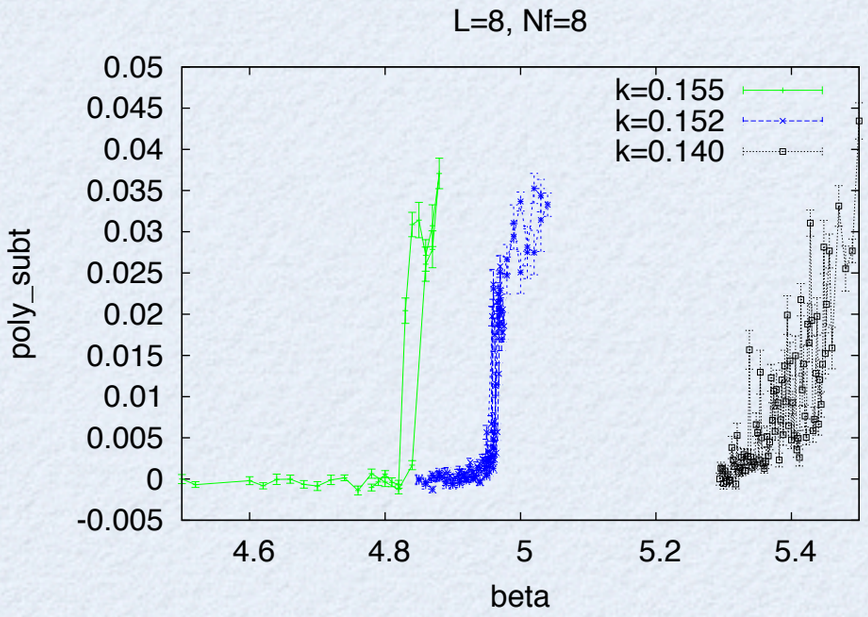
$V=8^3x8$, $N_F=6$-10

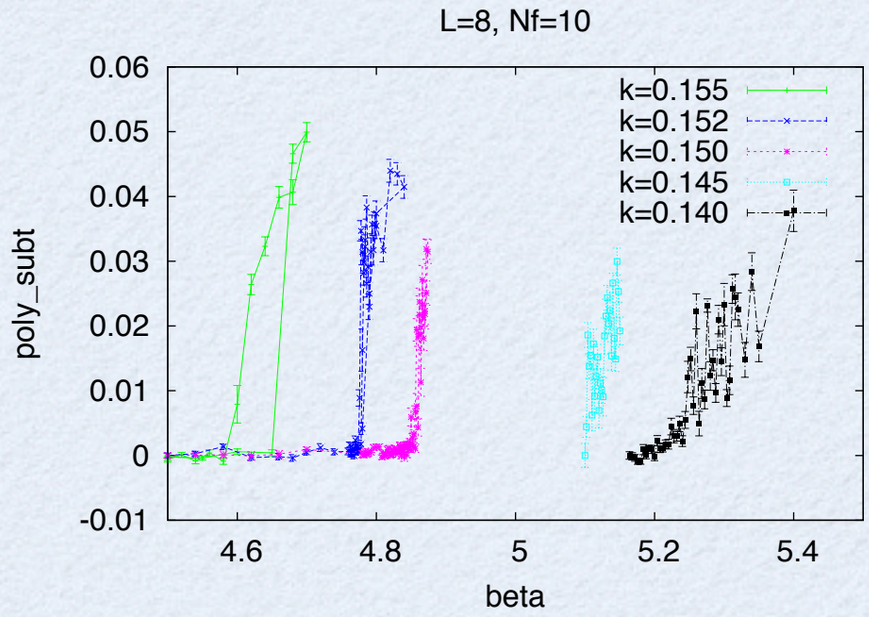
Preliminary Results for $N_F=6, 7, 8, 10$





1st order at large kappa weakens as going to small kappa.





Calc. on $V=16^4$ is on going.

(Far) Future plan

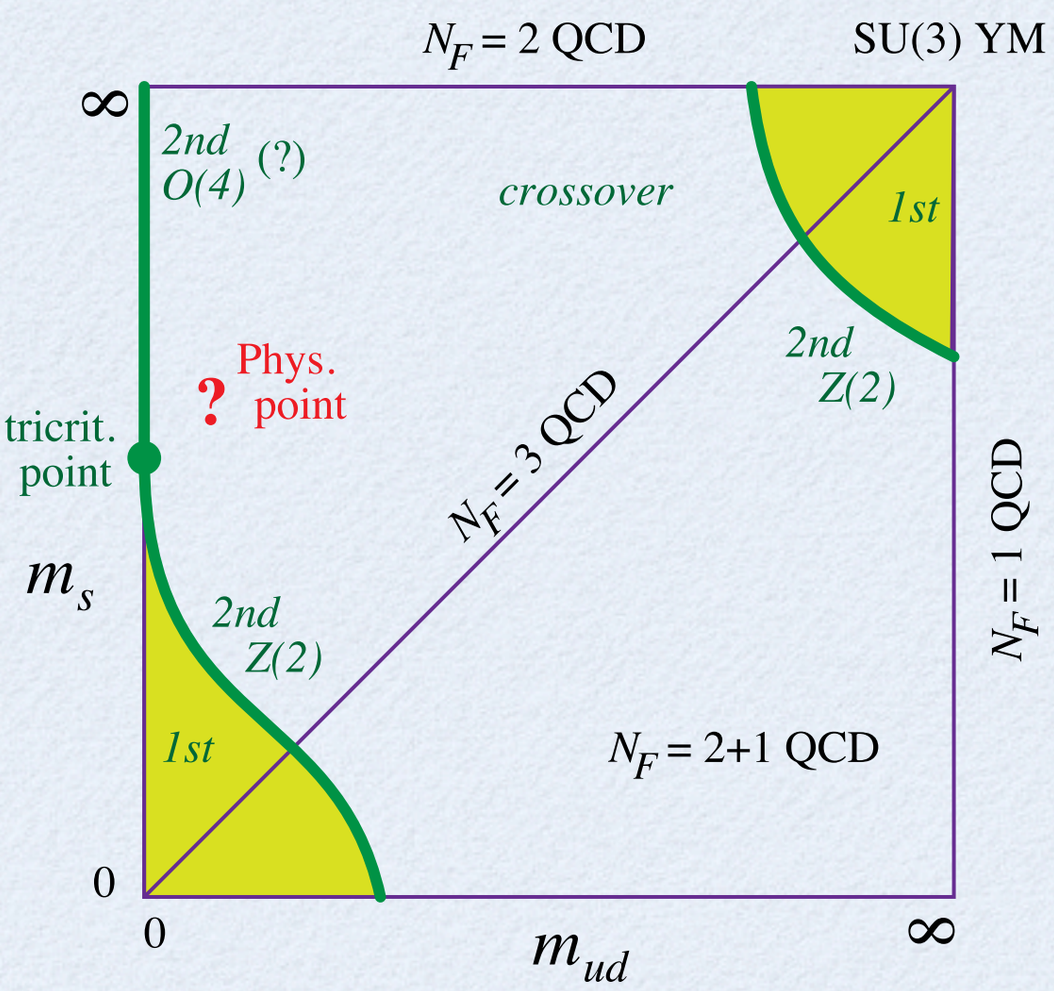
(strongly depends on what LHC@CERN observes.)

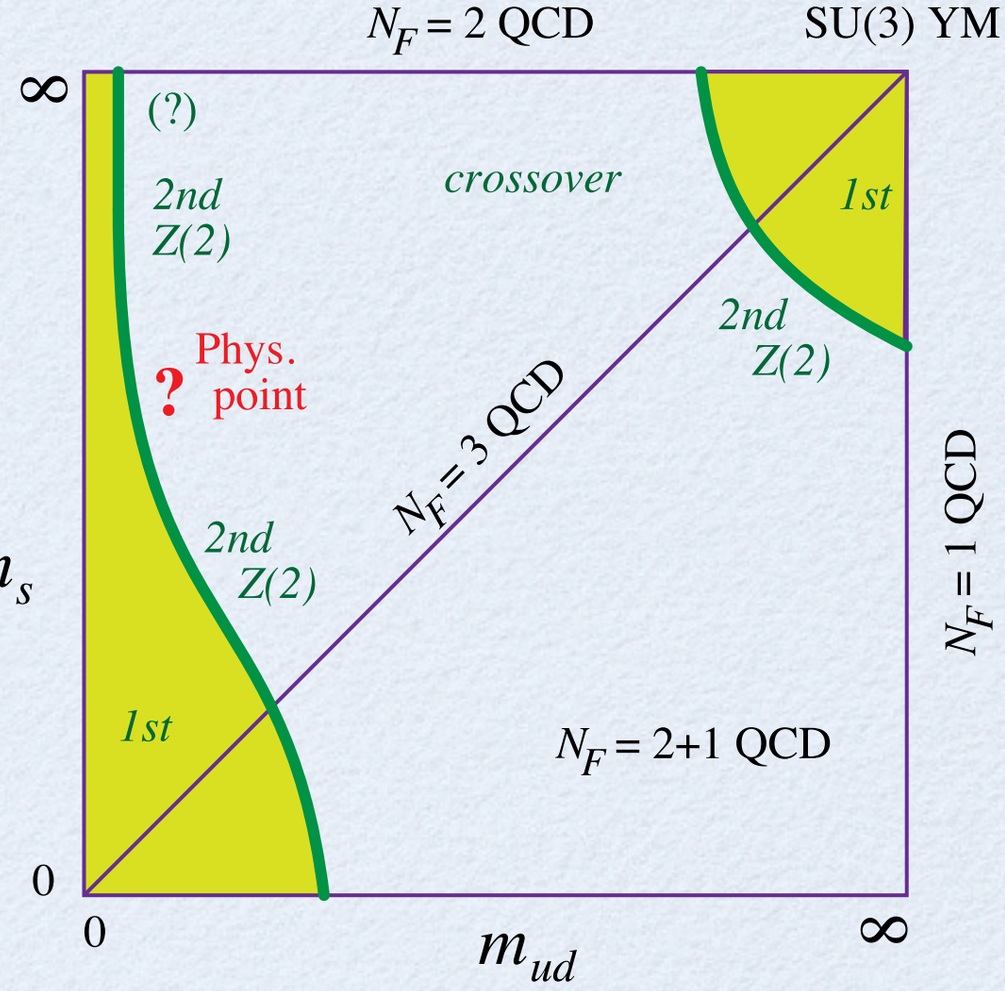
- ✓ In realistic TC model, only two of N_F flavors must be exact massless while the other N_F-2 flavors shouldn't be so.
- ✓ Go to 2 + (N_F-2) QCD
- ✓ Nice to discuss such a theory on the basis of Columbia plot

Columbia plot

Brown, Butler, Chen, Christ, Dong, Schaffer, Unger, and Vaccarino (90),
N.H. Christ, Z. Dong (92) and N.H. Christ(92)

Kanaya, Lattice 2010

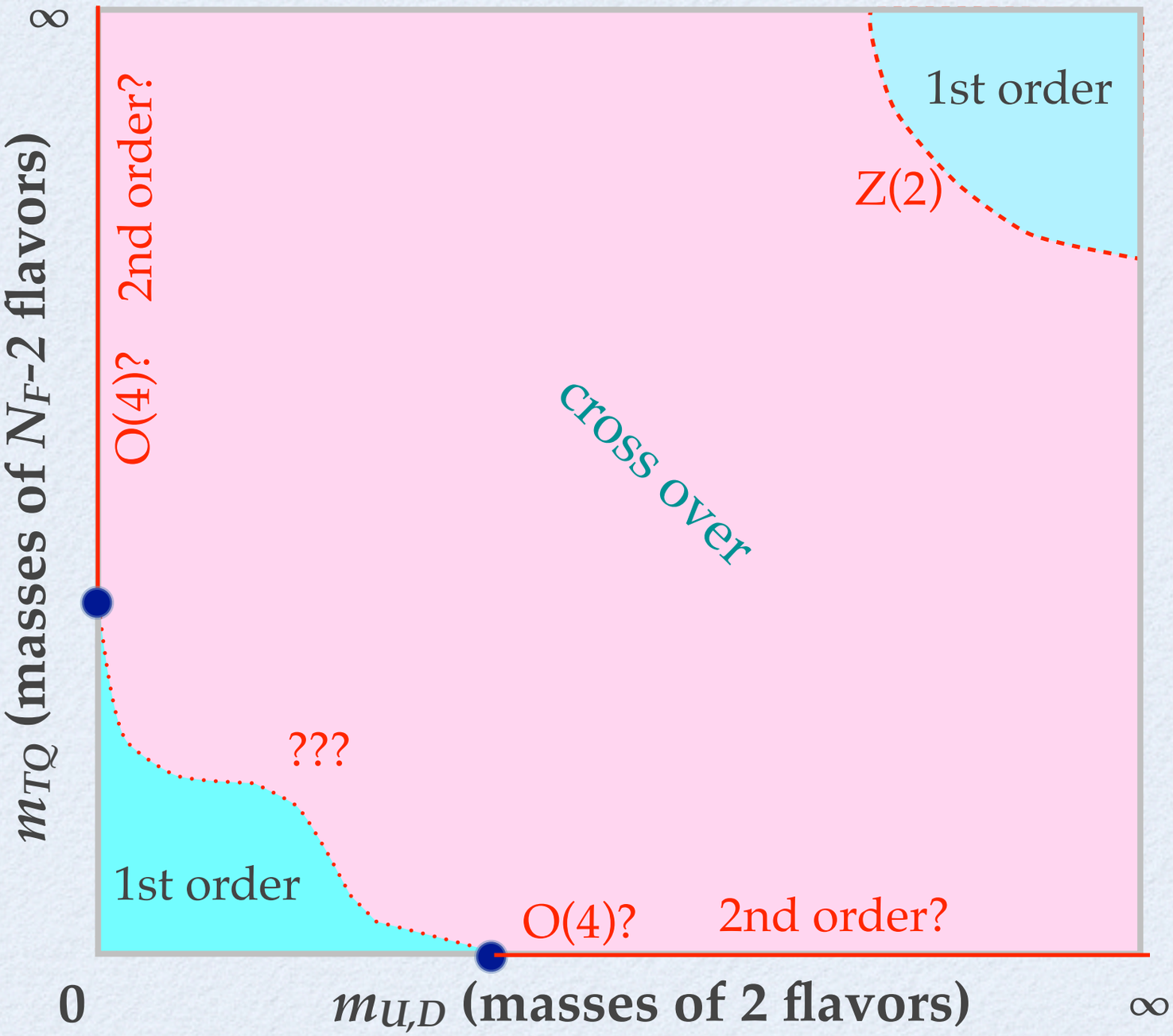




Recent lattice results seems to favor the left.

How does this plot for many flavor QCD look like?

$N_F = 4$ ($< N_F^{crit}$)



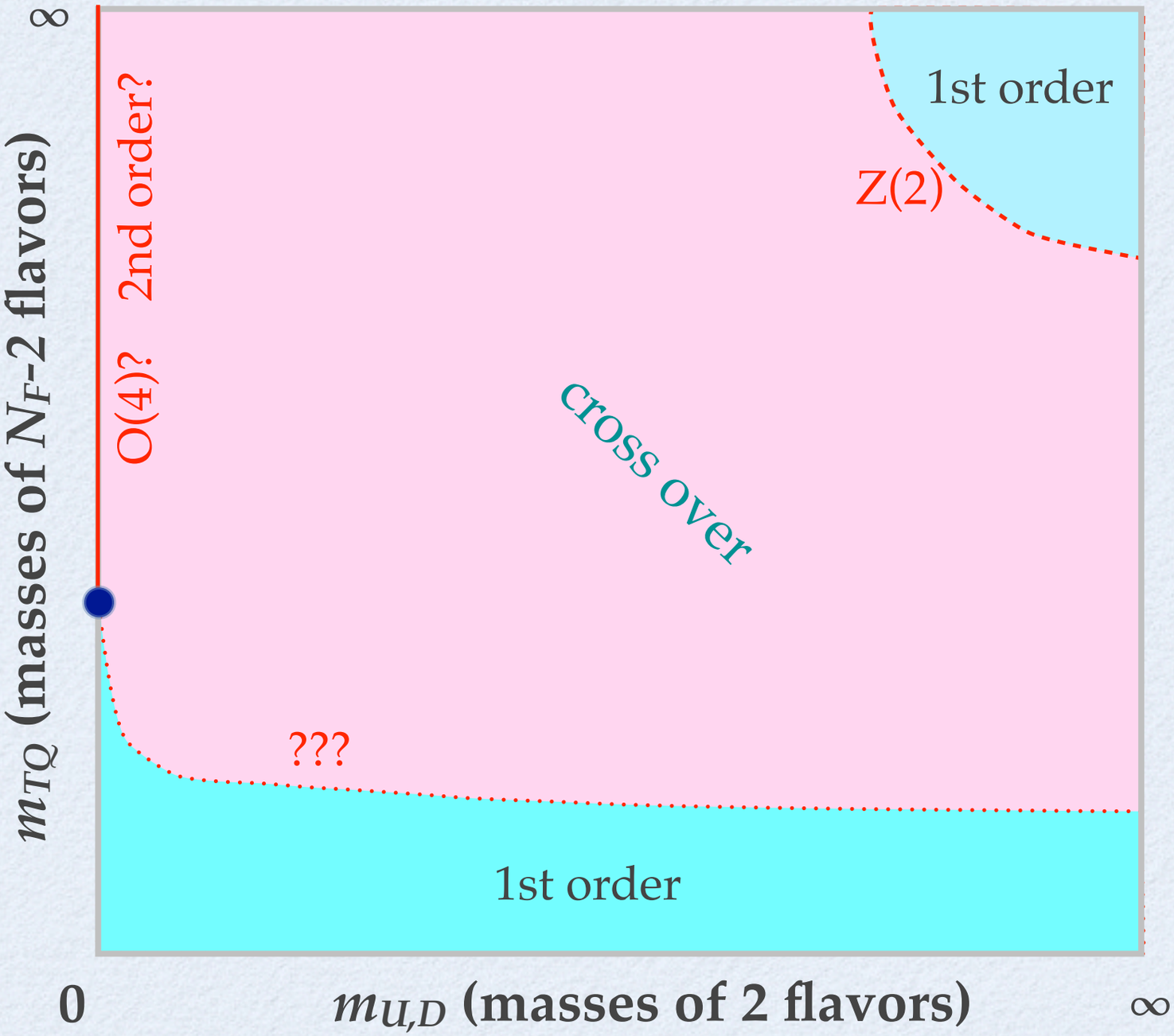
$N_F^{crit} > 4$ is assumed.

Symmetric phase diagram

Probably running is not slow enough.

Less interesting.

$5 \leqq N_F < N_F^{\text{crit}}$

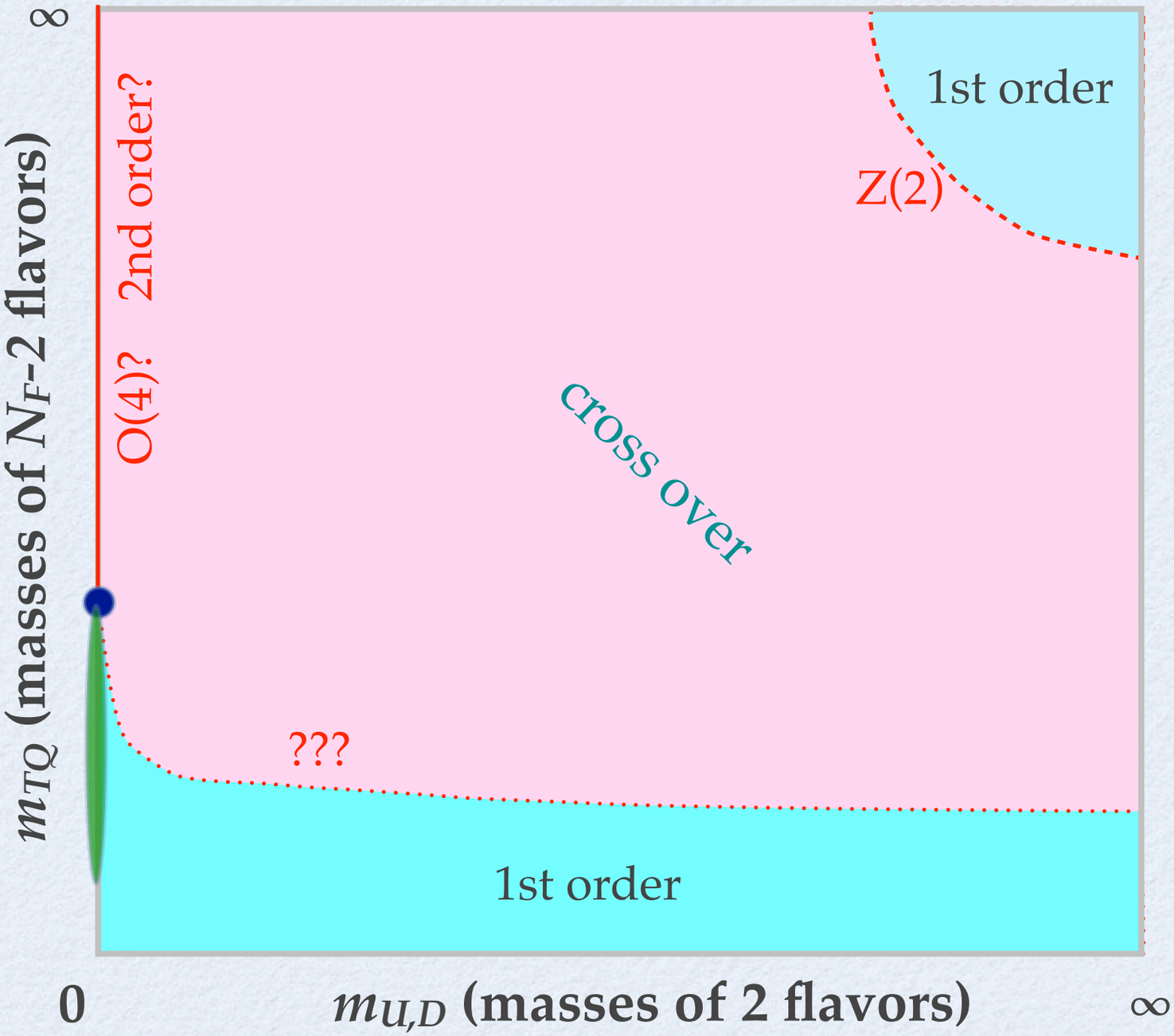


$N_F^{\text{crit}} > 5$ is assumed.

1st order persists to $m_{U,D} = \infty$ for small m_{TQ}.

Slow running and large γ_m may be expected at some N_F.

$5 \leqq N_F < N_F^{crit}$



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Slow running and large γ_m may be expected at some N_F.

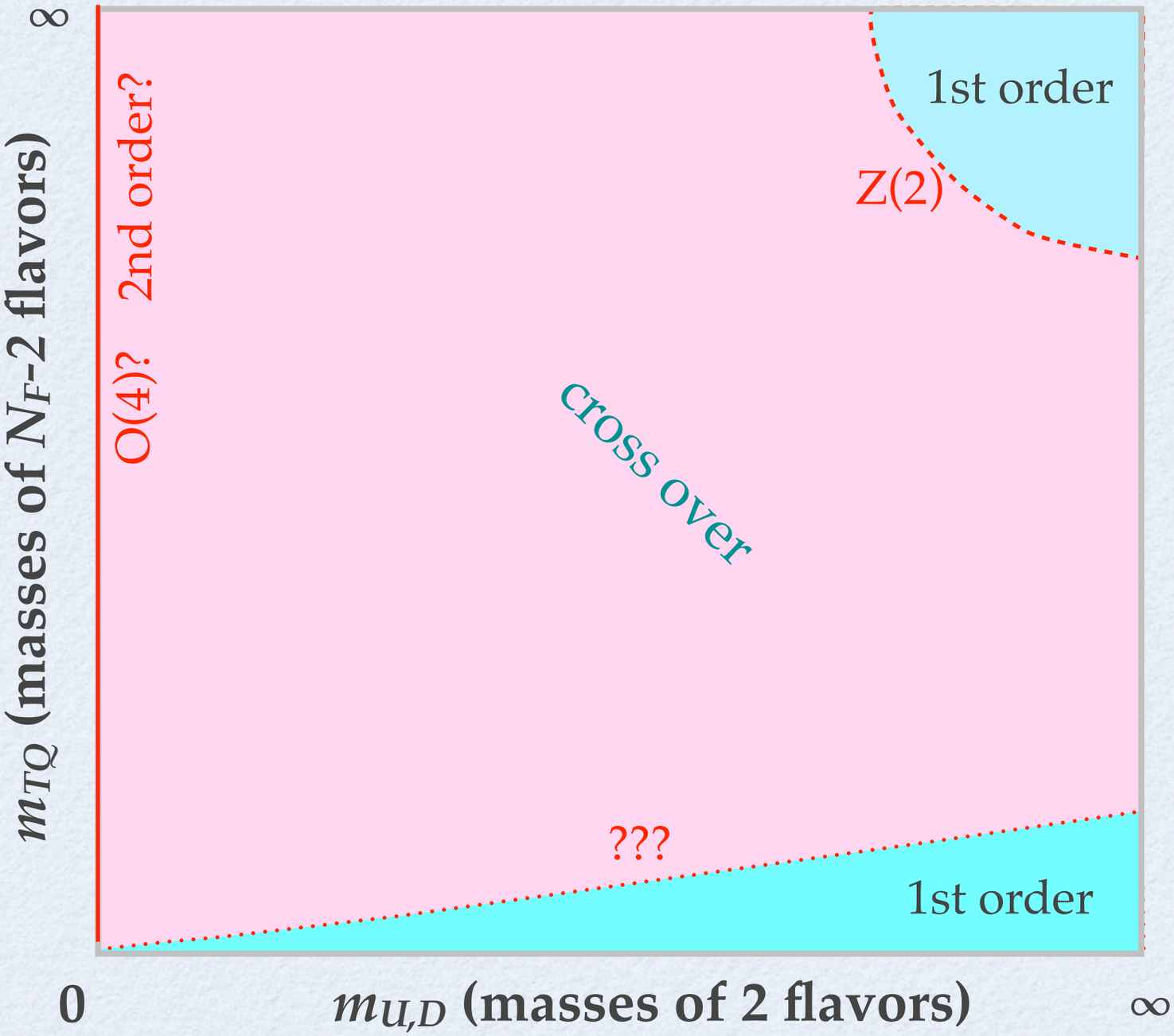
Furthermore,

- 1st order P.T. is attractive because of baryongenesis.

Appelquist, Schwetz and Selipsky, PRD52, 4741 (1995).
Kikukawa, Kohda and Yasuda, PRD77 (2008) 015014

Phenomenologically interesting!

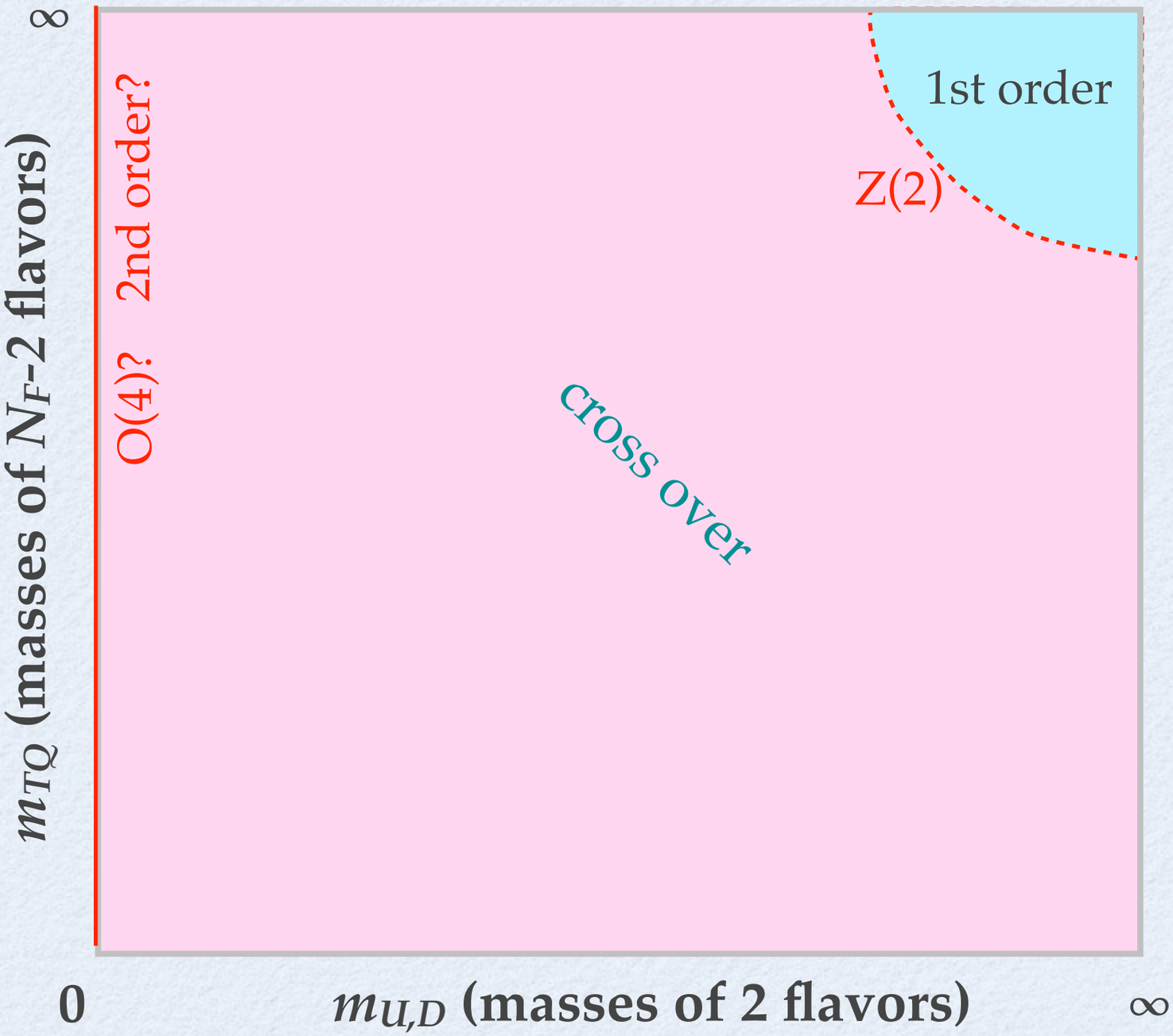
N_F - 2< N_F^{crit} < N_F (Speculation)



If this is the case,

EW Baryongenesis within TC seems to difficult.

$N_F^{crit} < N_F - 2 < N_F$ (Speculation)

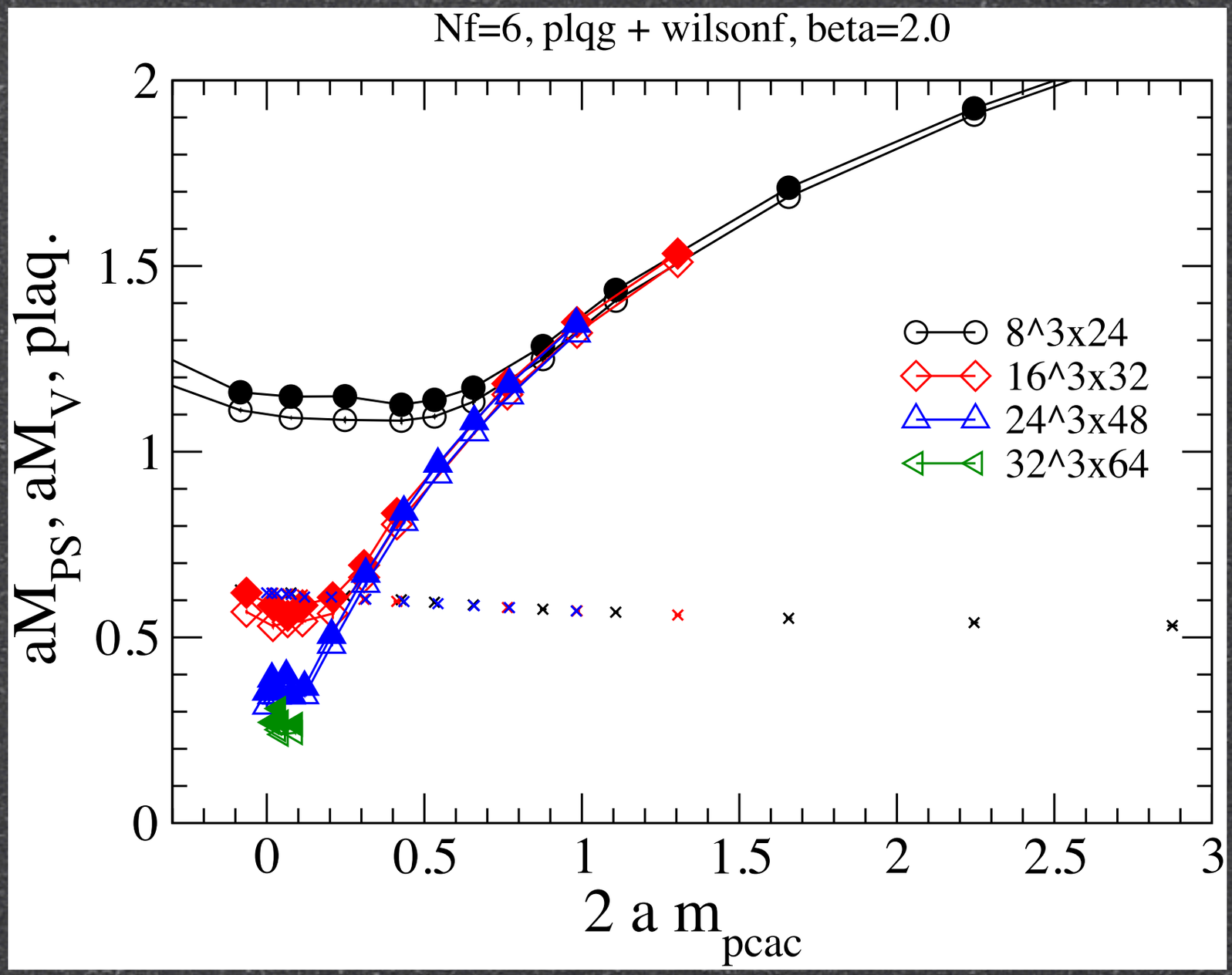


If this is the case, not interesting.

Summary

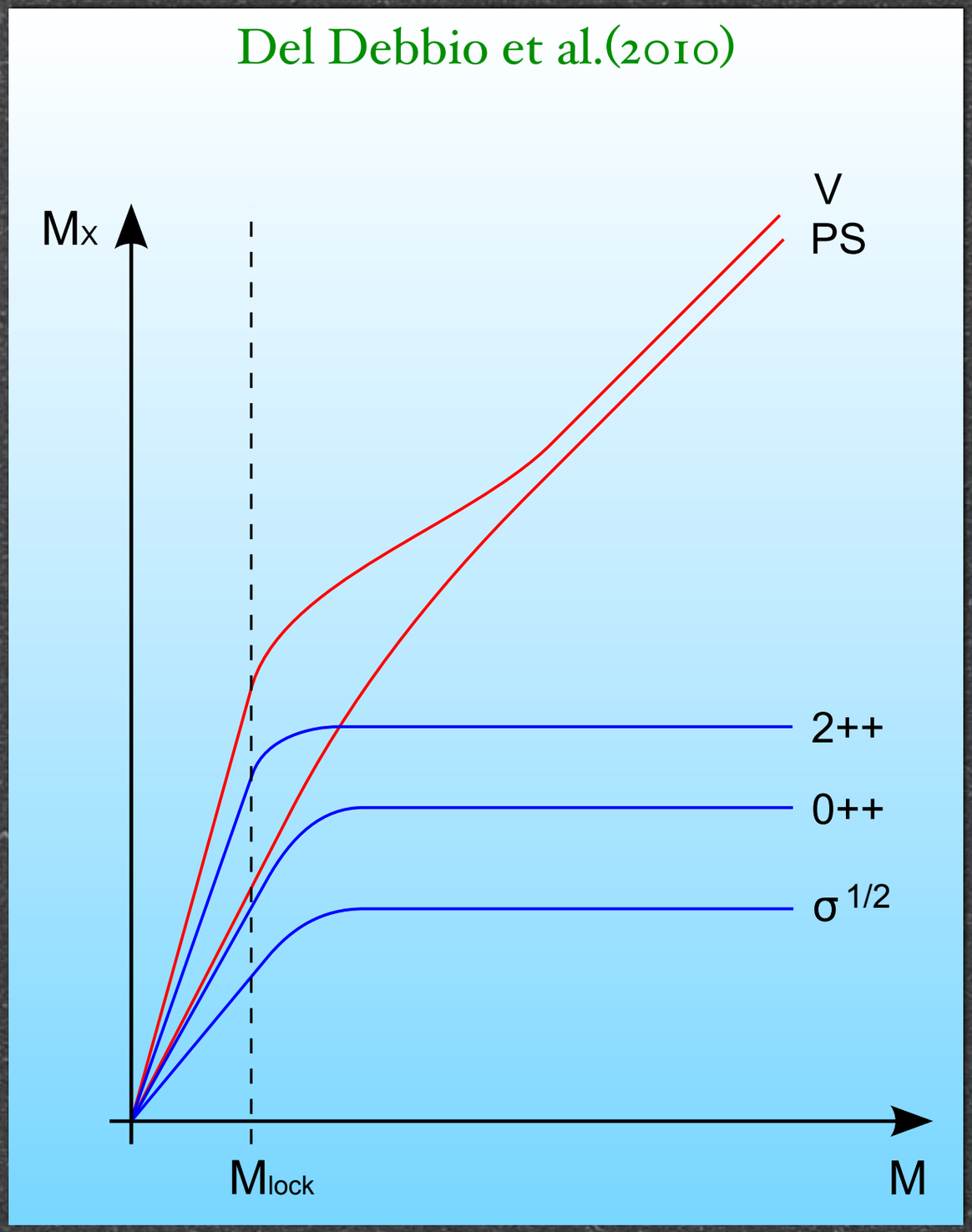
- ✓ Important to have several complementary approaches in the search for Conformal Window.
- ✓ We employ Wilson fermion to study the properties of Many Flavor QCD.
- ✓ Important to know Wilson Phase diagram when interpreting spectroscopy results.
- ✓ Establishing Columbia plot for Many Flavor QCD clarifies phenomenologically interesting region.

Finite Volume effect



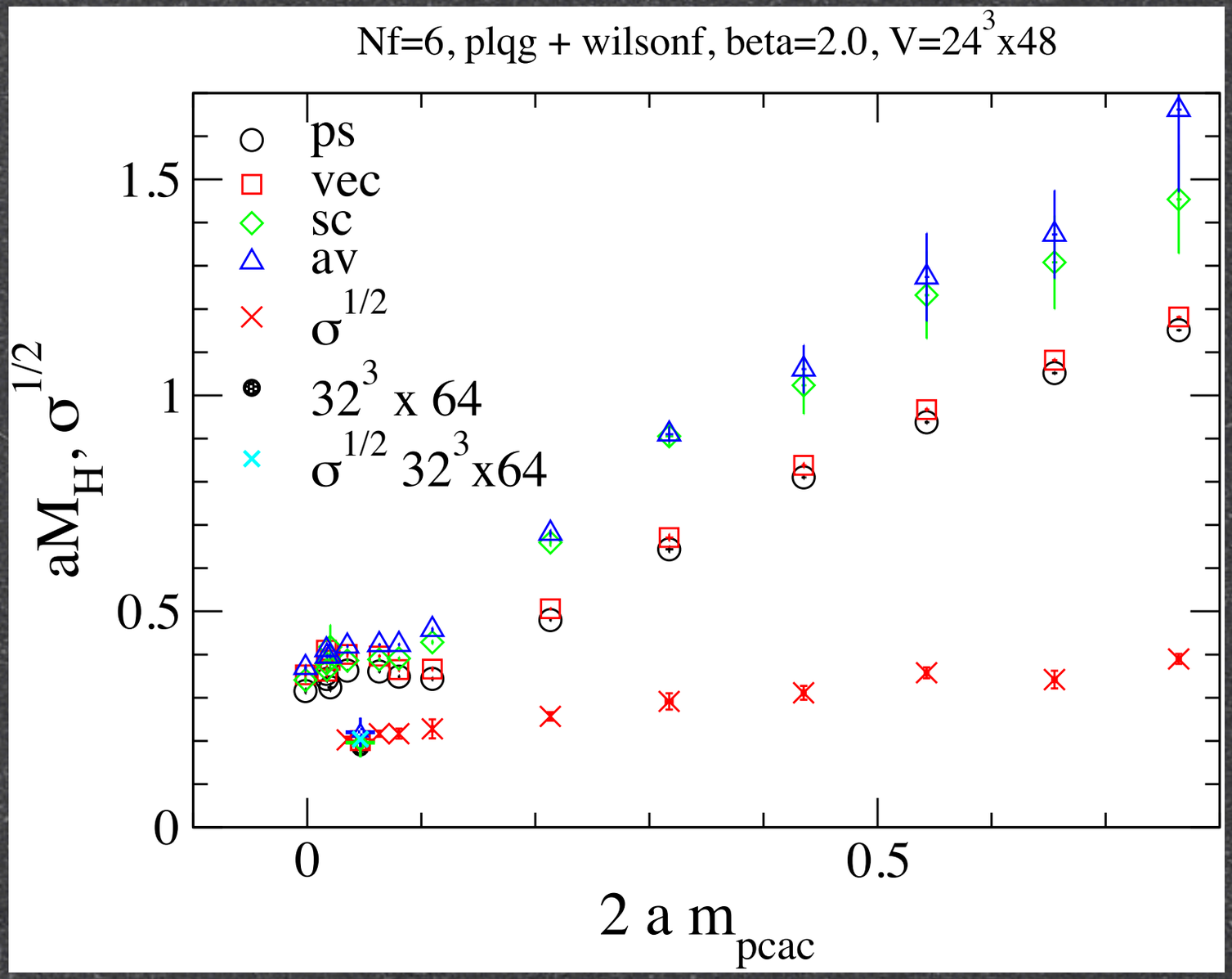
- Finite volume effect is significant.
- Masses are bounded from below.
- Minimum decreases as volume → large.

Expected behavior in Conformal Window



- Static limit = Quench
- In the massless limit, everything becomes massless.
- Dynamical scale (e.g. Λ_{QCD} in QCD) also vanishes there in contrast to QCD.
- Therefore, mass dependence of gluonic quantities is the key.

M_H and σ



- $M_P \approx M_V$ and $M_S \approx M_{AV}$ are typical pattern in the presence of heavy quark symmetry.
- $\sigma^{1/2}$ is smaller than M_H in most region.
- At $V=32^3 \times 64$, $\sigma^{1/2} \approx M_H$
- FVE is small for $\sigma^{1/2}$.
- $\sigma^{1/2}$ seems to remain finite in the chiral limit.
- Confinement?